Preliminary results of centroiding experiment for the STEP mission

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ABSTRACT

Search for Terrestrial Exo-Planet (STEP)[1] was originally proposed in 2013 by the National Space Science Center, Chinese Academy of Sciences, which is currently being under background engineering study phase in China. The STEP mission is a space astrometry telescope working at visible light wavelengths. The STEP aims at the nearby terrestrial planets detection through micro-arcsecond-level astrometry. Determination of the separation between star images on a detector with high precision is very important for astrometric exoplanets detection through the observation of star wobbles due to planets. The requirement of centroiding accuracy for STEP is 1e-5 pixel. A centroiding experiment have been carried out on a metrology testbed in open laboratory. In this paper, we present the preliminary results of determining the separations between star images. Without calibration of pixel positions and intra-pixel response, we have demonstrated that the standard deviation of differential centroiding is below 7.4e-3 pixel by the algorithm of linear corrected photon weighted means(LCPWM)[2,3]. For comparison, the photon weighted means(PWM) and Gauss fitting are also used in the data reduction. These results pave the way for the geometrical calibration and the intra-pixel quantum efficiency(QE) calibration of detector array equipment for micro-pixel accuracy centroiding.

KEYWORDS: STEP, exoplanets, centroiding, linear corrected photon weighted means, Gauss fitting

1. INTRODUCTION

In 1992, two planets around the pulsar PSR 1257+12 are discovered based on the timing measurements of the periodic variation of the pulsar's radio pulses[4]. The discovery of the first extra-solar planet surrounding a main-sequence star was announced in 1995 by measuring the periodic radial velocity variations of the steller reflex motion[5]. Several methods for detecting exoplanets have been developed: Doppler measurements, transit observations, microlensing, astrometry, and direct imaging and so forth. Since the discovery of 51 Peg b, an increasing number of planets and planetary candidates.

Most of the planets found outside the Solar System are gas giants, because they are more easily detectable. Better instruments and improved detection limits have pushed our capabilities towards the detection of low-mass and small planets. Although astrometry is the most ancient technique of astronomy, the technique has enormous potential and is complementary to other methods. Fortunately, with the successful launch of the Gaia satellite, the prospects for space-based astrometric planet searches are good. It will also pave the way for future space astrometry missions aiming at detecting the Earth-like planets around nearby stars[6].

The STEP mission aims at the nearby earth-alike planets detection, comprehensive research on the planetary system and the calibration of the cosmos distance with 1 μas astrometry precision in the space and get the fruitful achievements in the planetary and astrometry research fields. The FOV of STEP is 0.44×0.44 square degrees, based on 1.2m primary and focus length is 31m. The Cassegrain and TMA design(different from NEAT design[7-11]), mosaic APS and the laser metrology technique will be taken to achieve 1 μas astrometry precision[1].

The heterodyne laser interference metrology and the high precision centroiding is the key technology for the STEP. In this work, we will present the preliminary results of a centroiding experiment. The paper is organized as follows. The design of the experiment is presented in Sec. 2. In Sec. 3, the data reduction method and the results are presented. The discussion and summary are given in Sec.4.

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2. DESIGN OF THE EXPERIMENT

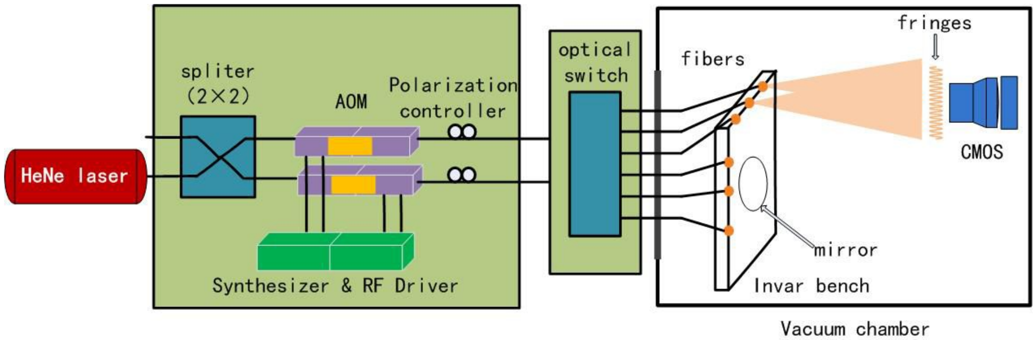

Figure 1. Schematic of the metrology and centroiding testbed.

The testbed contains two sub systems: the heterodyne laser interference system and the pseudo star system. A similar optical design appeared in the NEAT centroiding testbed[12-15]. The heterodyne laser interference system is used to calibrate the detector array equipment. The AOMs are introduced in the optical path to offset the frequency of two coherent laser beams. Thus the moving fringes can be generated on the detector. The moving fringes are used to calibrate the geometrical characteristics and the intra-pixel QE of the detector array. A white source and a single mode fiber bundle is used to generate the pseudo star source. With the spherical mirror reflecting the light onto the detector, several point spread functions can be obtained. The separations between these star images can be measured using many kinds of centroiding algorithms. The schematic of the metrology and centroiding testbed is shown in Figure 1. The parameters of the testbed is listed in Table 1.

Table 1. The main technical parameters of testbed.

Laser wave-length (nm)	Pupils of spherical mirror (mm)	Focal length (mm)	CMOS	Pixel size (μm)	No. of fiber cores	Wavelength of white source (nm)
632.8	5	600	2048×2048/ 960×1280	11×11/ 3.75×3.75	5	440-800

3. DATA ACQUISITION, REDUCTION AND RESULTS

Firstly, in order to demonstrate the image acquisition capability of the heterodyne laser interference system the metrology fringes are captured through a commercial camera with 960×1280 array. With these frames we evaluate the data quality. Secondly, the pseudo star images are captured. The separation between two of them is used as a metric in our experiment. We put the point spread functions (PSFs) on 51 different positions of the detector. Then the separation between two of them are measured 51 times and the standard deviation are calculated. While the dark frames and the flat field frames are captured.

3.1 The dark and flat field calibration

The first step is the dark field subtraction and flat fielding. We use the same exposure time with the fringe frames and the star field frames to obtain the dark frames. The flat field frames are obtained from the integrating sphere. The final data are derived through the dark subtraction and the flat fielding. The flat field response of a 380×650 pixel array is shown in Figure 2. These pixels are used to calculated the separation of the stars.

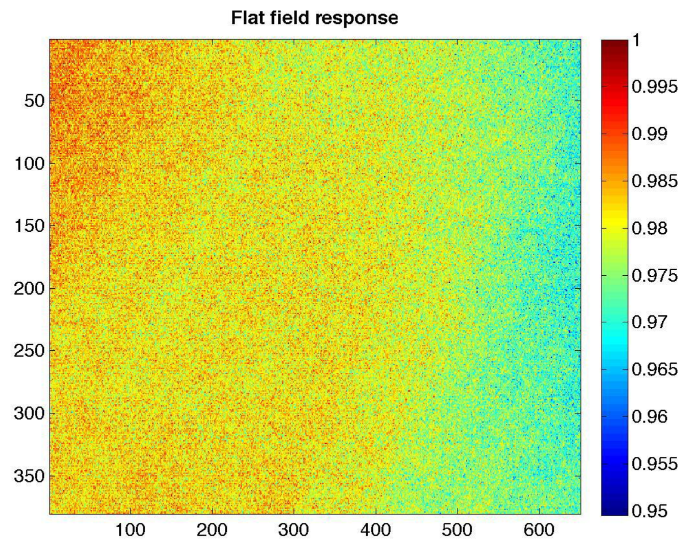

Figure 2. The flat field calibration result by integrating sphere. The area shown here contains 380×650 pixels. The peak to valley (PV) value is 0.0515. The standard deviation of photo-response non-uniformity(PRNU) is 0.0056.

3.2 The metrology fringes

Two orthogonal interference base lines are chosen, thus the orthogonal fringes are derived. Because the fringes move across the CMOS, every pixel on the detector will see a sine wave variation of the intensity. The fringes and the pixel intensity variation with time are shown in Figure 3 and 4.

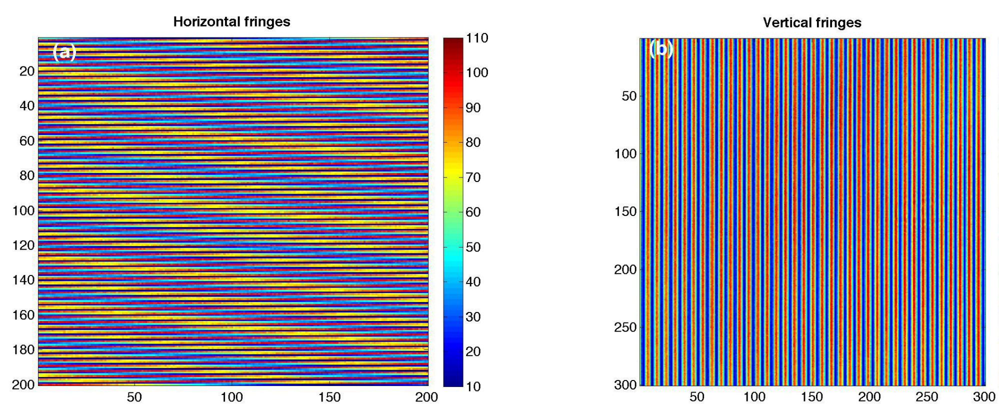

Figure 3. The horizontal fringes and vertical fringes. Two corners are shown here for clarity.

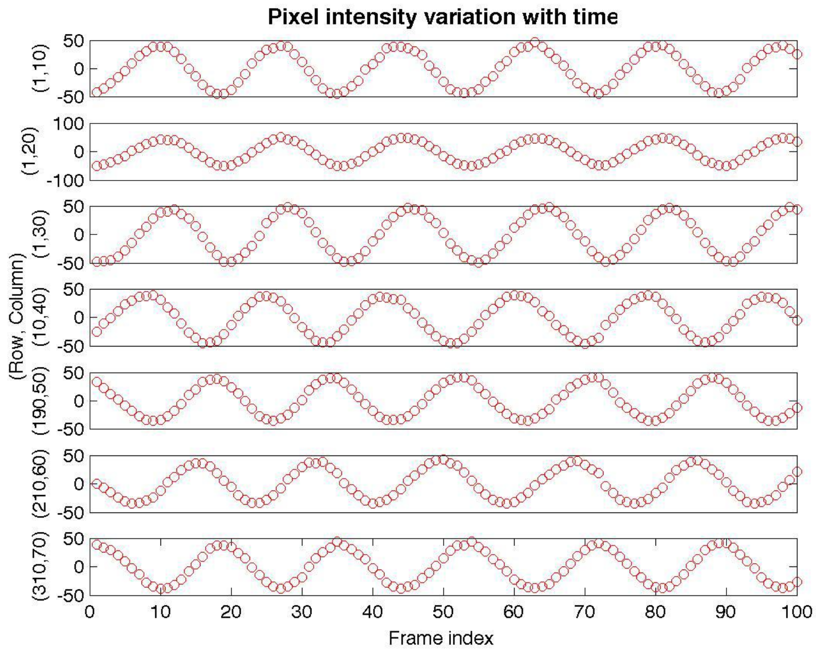

Figure 4. The sinusoidal waves of intensity variation for 7 randomly selected pixels from 1 fringe data cube.

3.3 The pseudo star field

In our experiment, 5 star images are obtained through a single mode fiber bundle. The star images are shown in Figure 5. As shown in Figure 5, we measured the distance between star A and star B. The star field is put on 51 different positions of the detector through the translation of the stage. The translation step is 10μm(~2.5pixel).

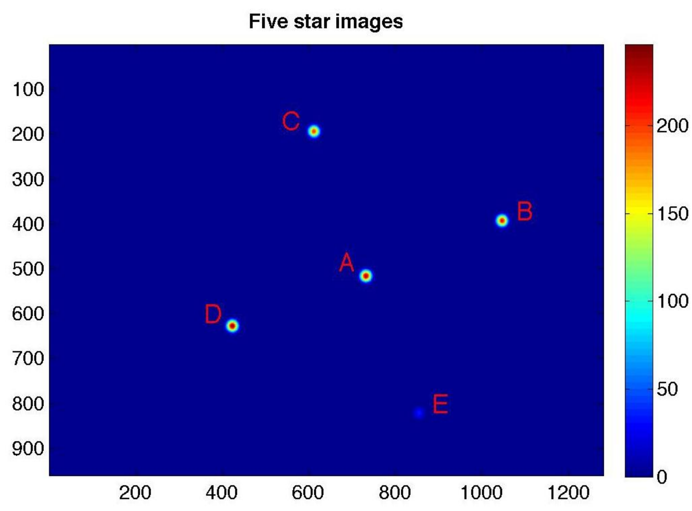

Figure 5. The pseudo star field from a single mode fiber bundle consist with 5 cores. For convenience, the five star images are labeled with A, B, C, D, E.

3.4 The centroid calculation

In the star field data reduction, we use three algorithms to do the calculation of the centroid, namely, the photon weighted means(PWM), the linear corrected photon weighted means(LCPWM)[2,3] and the Gauss fitting. The standard deviations are derived. We find that the standard deviation by LCPWM is the most smallest. There is a systematic

deviation between the Gauss fitting and the PWM/LCPWM for X differential centroid, but the fluctuation trend and the mean values of Y differential centroid calculated with the three algorithms are in good agreement.

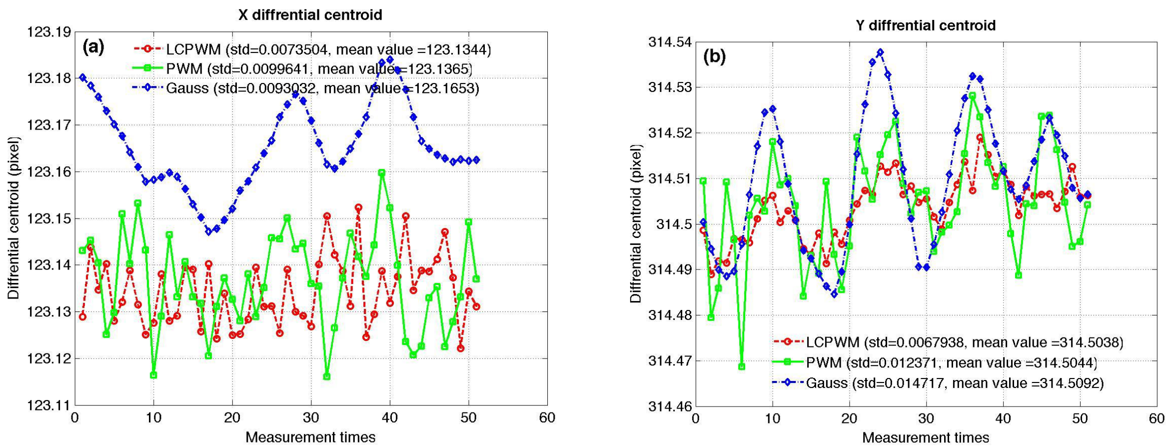

Figure 6. The X and Y differential centroid between star A and star B estimated through three algorithms (LCPWM, PWM, Gauss fitting) for 51measurements. The standard deviations are 0.0073504 pixel, 0.0099641 pixel and 0.93032 pixel respectively.

4. SUMMARY

We have carried out measurements of centroid of artificial star images on a CMOS detector to investigate the accuracy of the positions of the stars, using three algorithms for comparison. Finally, we have demonstrated that the standard deviation of the measurements for the differential positions of the star images is below 7.4e-3 pixels for 51 measurements. Follow-on investigations will include a more thorough characterization of back illuminated CMOS, such as the geometrical calibration and the intra-pixel QE calibration of the detector array.

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